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Size Dependent Model of Hazardous Substances in Aquatic Food Chain

Ecological Research Series

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A model of toxic substance accumulation is constructed that introduces organism size as an additional independent variable. The model represents an ecological continuum through size dependency; classical compartment analyses are therefore a special case of the continuous model. Size dependence is viewed as a very approximate ordering of trophic position.

The analysis of some PCB data in Lake Ontario is used as an illustration of the theory. A completely mixed water volume is used. Organism size is considered from 100 μm to 10^6 μm. PCB data were available for 64 μm net hauls, alewife, smelt, sculpin and coho salmon. The analysis indicated that about 30% of the observed 6.5 μg PCB/gm fish at the coho salmon size range is due to transfer from lower levels in the food chain and about 70% from direct water intake. The model shows rapid accumulation of PCB with organism size due principally to decreased excretion rates and decreased biomass at higher trophic levels. The analysis indicates that if a level of 5 μg PCB/gm at 10^6 μm is sought, total (dissolved and particulate) water concentration would have to be about 36 ng/l or about 66% of the present 55 ng/l.

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SIZE DEPENDENT MODEL OF HAZARDOUS SUBSTANCES IN AQUATIC FOOD CHAIN

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FOREWORD

The presence of Hazardous Substances in the environment is a major concern of the U.S. Environmental Protection Agency. One research goal of the Environmental Research Laboratory-Duluth is to develop quantitive methods for describing the transport and fate of hazardous substances in the freshwater environment, particularly the Great Lakes. High levels of persistant organic chemicals in Great Lakes fish are threatening their usefulness as a resource by jeopardizing the associated recreation and commercial fishing industries.

This report presents an innovative approach to tracking hazardous substances in freshwater ecosystems. It is a first attempt to conceptulize a very complex process. Additional research is required at this point to test and verify the hypothesis presented. The purpose of reporting this research in its infancy is to stimulate thinking by the research and management communities.

William L. Richardson
Environmental Scientist
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ABSTRACT

In order to incorporate both bioaccumulation of toxic substances directly from the water and subsequent transfer up the food chain, a mass balance model is constructed that introduces organism size as an additional independent variable. The model represents an ecological continuum through size dependency; classical compartment analyses are therefore a special case of the continuous model. Size dependence is viewed as a very approximate ordering of trophic position.

The analysis of some PCB data in Lake Ontario is used as an illustration of the theory. A completely mixed water volume is used. Organism size is considered from 100 μm to 10^6 μm. PCB data were available for 64 μm net hauls, alewife, smelt, sculpin and coho salmon. Laboratory data from the literature were used for preliminary estimates of the model coefficients together with the field data. The analysis indicated that about 30% of the observed 6.5 μg PCB/gm fish at the coho salmon size range is due to transfer from lower levels in the food chain and about 70% from direct water intake. The model shows rapid accumulation of PCB with organism size due principally to decreased excretion rates and decreased biomass at higher trophic levels. The analysis indicates that if a level of 5 μg PCB/gm at 10^6 μm is sought, total (dissolved and particulate) water concentration would have to be about 36 ng/l or about 66% of the present 55 ng/l.

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SECTION 1

INTRODUCTION

The presence of hazardous substances in the aquatic food chain is a problem of rapidly developing dimensions and magnitude. Passage of the Toxic Substances Control Act of 1976, unprecedented monetary fines, and continual development of data on lethal and sub-lethal effects attest to the expansion of control on the production and discharge of such substances. On the other hand, new product production and the ever present potential for insect and pest infestations with attendant effects on man and animal result in continuing demand for product development. As a result of this confrontation, considerable effort has been devoted in recent years to the development of predictive schemes that would permit an a priori judgment of the effects of a given substance on the environment.

In this paper, a model is presented that is focused specifically on the aquatic ecosystem and the transport and accumulation of hazardous substances in the aquatic food chain. Specific toxicological effects are not included in this work; the emphasis is on the fate of the substance in the aquatic ecosystem. The primary motivation for the development of the model is to place in a generalized framework, the large amount of work in laboratory, field, and mathematical experiments of hazardous substances in the food chain.

The literature on the transport of hazardous substances generally begins by assigning to the ecological system a series of compartments positioned in space and time. The concept of a compartment arises from a grouping of ecological properties, species or types (e.g., "phytoplankton", "fish"). The continuum of the environment is replaced by finite, discrete, interacting trophic levels. The details of each compartment need not be specified and internal mechanisms are not necessarily examined. Attention is usually directed towards a portion of the ecosystem, the degree of specificity of compartments depending heavily on the aims of the investigator. The ecological concepts of compartment analyses have been reviewed by Dale (1970), and Patten (1971). Examples of compartment models in food chain studies of hazardous substances include Gillet (1974), Hill et. al., (1976), Lassiter, et. al., (1976) and Hoefner and Gillet (1976).

Compartment analyses provide a great deal of flexibility and can incorporate reasonably complicated food webs. However, the basic difficulty with viewing the food chain problem in a compartment sense is that any general underlying theoretical framework may be masked by the choice of the compartment. The discretization of the aquatic food chain obscures the "continuous" nature of the ecosystem. Futhermore, if there are m ecological variables

(ecological compartments) positioned at n spatial locations, there are a total of m x n compartments and m x n equations (differential or algebraic) to be solved. Thousands of equations can easily result. The thrust of this work therefore is the formalization of a generalized unified framework for the transport of substances in the food chain. Discretization of ecological space into compartments would therefore be a special case or approximation of the general theory.

SECTION 2

CONCLUSIONS

As a result of the research reported on herein, the following conclusions can be drawn.

1. The one-dimensional aquatic food chain can be visualized as a continuum using organism length as an independent variable.

2. The mass balance of a toxicant being both absorbed directly from the water and transported up the food chain by predation, using an organism length representation, results in a single partial differential equation, the properties of which are well-known.

3. This equation in principle permits rapid solution for the distribution of the toxicant throughout the food chain without resort to classical compartment analysis and resulting sets of equations. However, the size dependent model in its present form, does not permit detailed analysis on any one segment of the ecosystem.

4. The size dependent model provides a framework for uptake, feeding and excretion data by aquatic organisms coupled to the physical properties of the water body (flow, volume) and the chemical properties of the toxicant (photo-oxidation, vaporization).

5. An illustration is provided by PCB concentration over the size range from 100 μm to 10^6 μm. Using the observed PCB distribution in a food chain of Lake Ontario, a calibration of the model coefficients indicates that 67% of the observed 6.5 μg/gm in coho salmon is from direct uptake from the water phase and 33% from the food chain route.

SECTION 3

RECOMMENDATIONS

It is recommended that additional hazardous substances be investigated within the size dependent model structure to determine food chain accumulation patterns. Such substances might include cadmium, mercury, and mirex, among others. Additional problem settings should also be investigated including small lakes or embayments, and river and estuarine systems.

Further, it is suggested that the relationship of the size dependent model and compartment models be investigated together with the interaction of the size dependent model and biomass models.

SECTION 4

THE GENERALIZED MODEL

The principal questions that prompted this line of research into a generalized hazardous substance model are: "If compartments represent discrete, homogenous entities in ecological space, what is the continuous analog of this approximation? Since compartment analyses often represent differential equations around previously chosen trophic levels what is the suitable mathematical framework that would represent ecological space as a continuum rather than discretized levels?" Figure 1 illustrates the question by analogy to the often-made discrete approximation to a continuous water body for analysis of dissolved substances in the water. Continuous space is replaced by a series of discrete regions in space and mass balance equations are written around each region in space for the substance of interest. Similarly in ecological compartment analyses, mass balance equations are written around a series of individual "regions" thereby describing the transport and cycling of the substance in the food chain. For a toxicant, the relevant measure is the mass of toxicant per unit biomass at that level.

COMPARTMENT APPROACH

Therefore, for compartment analyses, one lets

$$\nu_{ij} = \left(\frac{\text{mass toxicant}}{\text{mass trophic level i}}\right)$$

at location j and

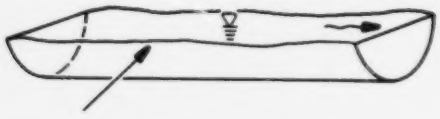
$$M_{ij} = \left(\frac{\text{mass of trophic level i}}{\text{volume of water}}\right)$$

also at location j. Then $\nu_{ij}M_{ij} = s_{ij}$ is the mass of toxicant of level i relative to the volume of water at location j. In one-dimensional food chains (excluding food webs for the moment), for a volume of water V_j, the rate of change of the mass of the toxicant is given by:

$$V_j \frac{d\nu_{ij}M_{ij}}{dt} = (K_{i-1,i}M_{i-1}\nu_{i-1})_j V_j) - (K_{ii}M_i\nu_i)_j V_j \qquad (1)$$

$$+ \text{advection} + \text{dispersion} + \text{sources} - \text{sinks}$$

where $K_{i-1,i}$ and K_{ii} are transfer rates $[T^{-1}]$ into and out of level i.



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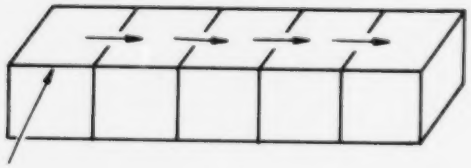
DISCRETE APPROXIMATION



(a) Transport of substance in water.

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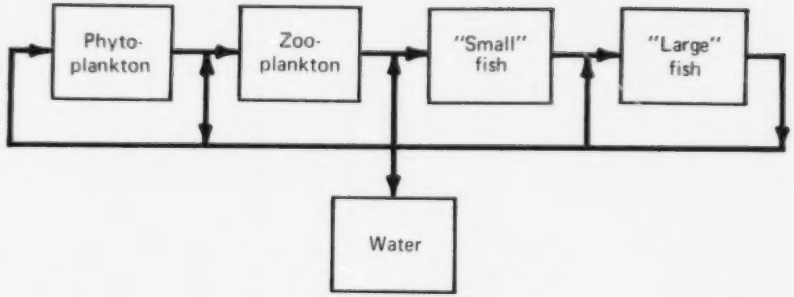
CONTINUOUS

DISCRETE APPROXIMATION



(b) Transport of substance in food chain.

Figure 1. The Continuous Environment and Discrete Approximation

If it is assumed temporarily that the mass/volume of each trophic level is constant and that there is a single completely mixed volume, then Equation (1) becomes:

$$M_i' \frac{d\nu_i}{dt} = S_{i-1,i}\,\nu_{i-1} - S_{ii}\nu_i + W_i \qquad (2)$$

where $M_i' = M_i V$ = trophic level mass, $S_{i-1,i} = K_{i-1,i} M_{i-1}$, $S_{ii} = K_{ii} M_i$ and W_i = external sources and sinks. (Advective and dispersive terms can, of course, be included). Now, it is noted that Equation (2) is identical to the mass balance equation that results for a finite difference approximation for water quality variables in physical space. In Equation (2), however, physical space is replaced by trophic space or ecological space. The question posed earlier is thus made specific by Equation (2), i.e., what is the underlying continuous equation of which Equation (2) is an approximation?

The subscript i in Equation (2) essentially represents some ecological variable in continuous trophic space. Therefore, in reality, Equation (2) represents a mass balance around some region in ecological space represented by an ecological coordinate. Such a coordinate would be distinct from the usual physical coordinates of length, width and depth of a water body. A generalized model would proceed by writing a mass balance equation that incorporates both physical and ecological space. Such a derivation is part of a class of models generally referred to as "Population Balance Models" because of their use in describing age distributions. A detailed review of such models is given by Himmelblau and Bischoff (1968) and Rotenberg (1972).

CONTINUOUS MODEL

Following these authors, consider a function $\Psi(\Delta x, \Delta y, \Delta z, \Delta\xi_1, \Delta\xi_2 \ldots \Delta\xi_m)$ where Δx, Δy, Δz represent in the usual sense, the physical coordinates and the ξ's represent other properties of the system. In some applications, this may be the age of a population or the size of suspended particles. Then,

$$\Psi(\Delta x \Delta y \Delta z \Delta\xi_1 \ldots \Delta\xi_m)$$

represents the fraction of some quantity (in this work, a toxicant of interest) that is in the physical region volume element $\Delta V = \Delta x \Delta y \Delta z$ and also is in the property range of $\Delta\xi_1 \ldots \Delta\xi_m$. If a general mass balance of the toxicant throughout both physical and "property" space is carried out (see Himmelblau and Bischoff), one obtains

$$\frac{\partial\Psi}{\partial t} + \frac{\partial}{\partial x}(v_x\Psi) + \frac{\partial}{\partial y}(v_y\Psi) + \frac{\partial}{\partial z}(v_z\Psi) + \sum_{i=1}^{m} \frac{\partial}{\partial i}(v_i\Psi) = \begin{matrix}\text{Sources} \\ \text{and Sinks}\end{matrix} \qquad (3)$$

where $v_x = dx/dt$, $v_y = dy/dt$, $v_z = dz/dt$ and $v_i = d\xi_i/dt$, the time rate of change of the property i. Equation (3) is the general mass balance equation for a toxicant in m+3 space and can be compared to the usual three-dimensional

mass balance equation written only in physical space. In the case of food chain modeling, a relevant metric must be chosen that can represent position in trophic space. One such measure is the size or length of the organism which through suitable allometric relationships can be related to the mass of the organism (see Eberhardt, 1969). The choice of organism size as a suitable metric in trophic space is advantageous from a field sampling point of view. That is, it is considerably less difficult to fractionate samples by size than by weight. Nets and filters can be easily used to divide a food chain by size. An example of the continuous nature of the ecosystem is shown in Figure 2. The overlapping size preferences of various stages of the alewife illustrates the role that organism size plays in food chain transfers. Futhermore, if there is no change in species composition, the length metric may be related to the lipid content of organisms which may be of value in the modeling of lipophilic compounds.

Of course, the use of an overall length metric does not permit a distinction to be made between organism types. Therefore, fish larvae and large crustaceans look the same to this metric: "a centimeter is a centimeter". It should be recognized also that introducing size dependence as an independent variable greatly oversimplifies a complex ecosystem. Such dependence implies that larger organisms prey on smaller organisms which is obviously not always true. The framework given below, however, in principle permits different size class interactions, but this is not pursued in this work. For certain problem contexts, organism size may be very roughly correlated to trophic position, but it is recognized that in general, trophic status and organism size are not related. The approach here is to introduce an ecologically reasonable simplification into existing model structures to provide additional analytical insight.

Conceptually, incorporation of other ecological properties is readily accomplished in Equation (3) but obviously at the sacrifice of analytical simplicity. The idea then is to describe the transport of a hazardous substance by how much of the total mass of the substance is located at various size ranges of organisms and in various locations in physical space. For organism size and one physical dimension, say longitudinal distance, Figure 3 shows the nature of Ψ. As indicated, Ψ is a density function of the toxicant for positions x and property ξ. The transport with organism size is considered as one-dimensional and not branched, such as in a food web. For a one-dimensional food chain

$$\Psi = s\ f(L,t)$$

where s = mg toxicant/liter and f dL = fraction of total mass of toxicant between trophic length L and L + dL, so that Ψ has units [mg toxicant/liter-organism length]. Note that since Ψ is a continuous density function, the amount of toxicant mass at a specific size is zero; only over some range of organism size is there a non-zero amount of toxicant mass. This is a consequence of the assumption that biological space is described by a continuum of organism size. The special case of single organism aquaria experiments is easily derived from this general view.

For a one dimensional size distribution and using the standard dispersion and advective terms in physical space, Equation (3) becomes

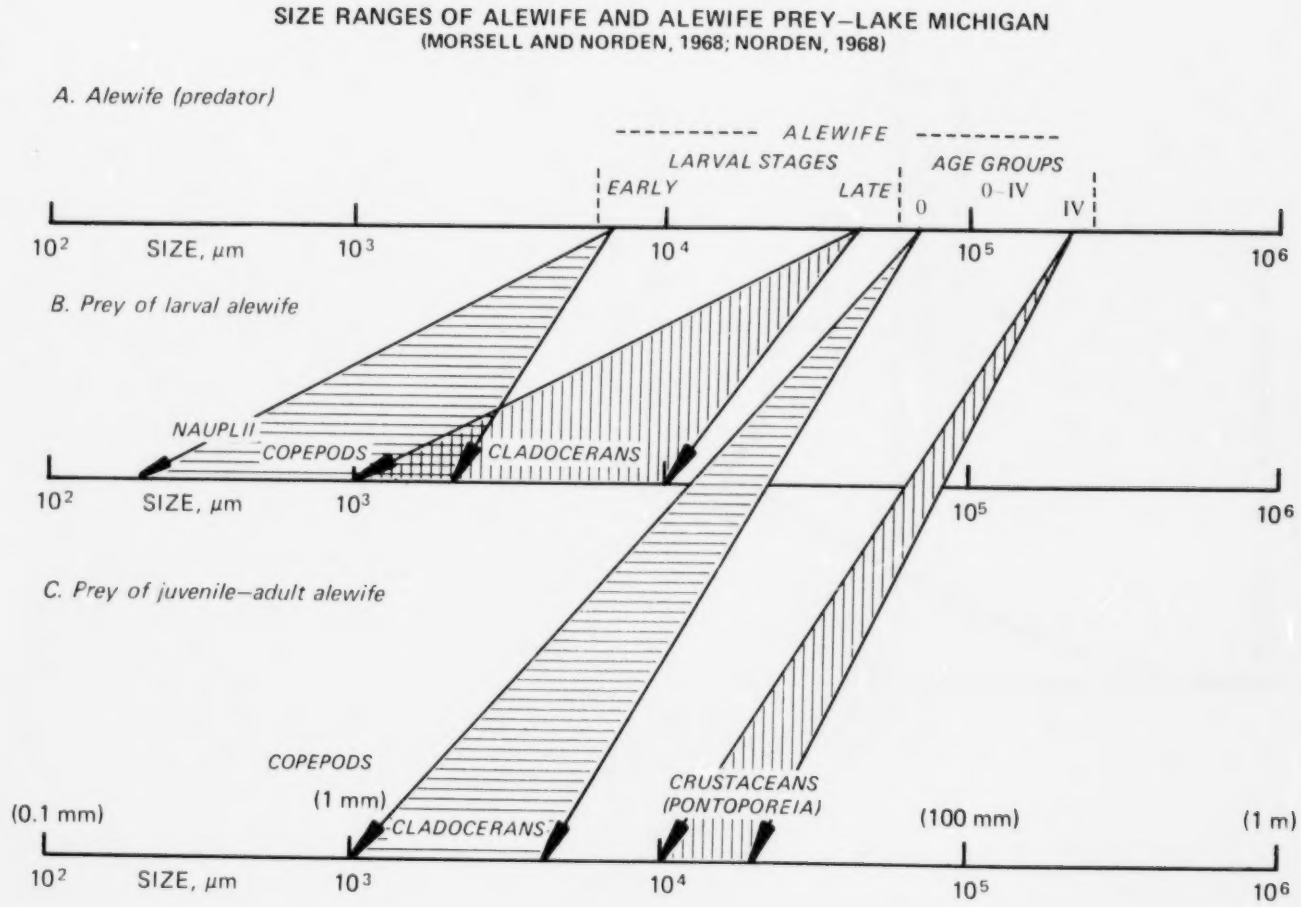


Figure 2. Range of Prey Size for Alewife Larval Stage and Juvenile-Adult Age Groups 0-IV, Lake Michigan

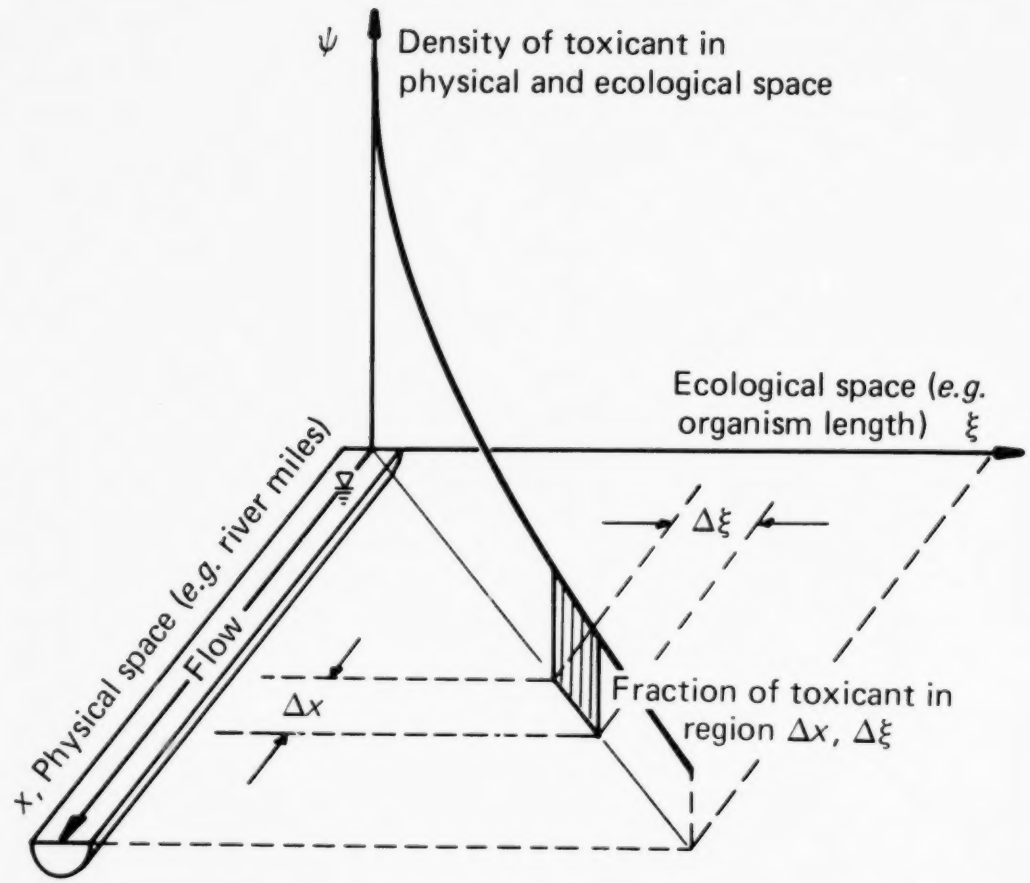


Figure 3. Distribution of Toxicant in One-Dimensional Physical and Ecological Space

$$\frac{\partial \Psi}{\partial t} + \frac{\partial}{\partial x}(v_x \Psi) + \frac{\partial}{\partial y}(v_y \Psi) + \frac{\partial}{\partial z}(v_z \Psi) + \frac{\partial}{\partial x}(E_x \frac{\partial \Psi}{x}) + \frac{\partial}{\partial y}(E_y \frac{\partial \Psi}{\partial y}) + \frac{\partial}{\partial z}(E_z \frac{\partial \Psi}{\partial z}) + \frac{\partial}{\partial L}(v_L \Psi) = S\ (x,y,z,L,t) \tag{4}$$

where v_x, v_y, v_z are net advective velocities in xyz, respectively, E_x, E_y and E_z are dispersion coefficients in xyz space, S represents the sources and sinks of Ψ, and $v_L = dL/dt$, the "transfer velocity" with which the toxicant is transported up the food chain represented by the metric, L.

A separate equation is necessary for the water phase of the toxicant and is given by

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(v_x c) + \frac{\partial}{\partial y}(v_y c) + \frac{\partial}{\partial z}(v_z c) + \frac{\partial}{\partial x}(E_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(E_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(E_z \frac{\partial c}{\partial z}) = W\ (x,y,z,t) \pm \int_0^\infty S'(x,y,z,L,t)dL \tag{5}$$

where W is the direct input of the hazardous susbstance to the water body from external sources (independent of Ψ) and $\pm S'$ is the source or sink of c due to uptake and excretion mechanisms in biological space. Note that Equation (5) does not include the L dimension as an independent variable and also that if sediment interactions are to be included, a separate sediment equation must be written to provide input to the water phase of Equation (5). Figure 4 schematically shows the various interactions in the model for a single completely mixed volume of water. As indicated, the concentration in the completely mixed volume is interactive with a continuous distribution along the L dimension. Thus, as shown in Figure 5, the mass of the toxicant is given by the area between L_1 and L_2 or the cumulative mass distribution along L is given by s_c as

$$s_c = \int_0^L \Psi(L')dL' \ [M/L^3] \tag{6}$$

The total toxicant mass along the entire size range (s_T) is then given by

$$s_T = \int_0^\infty \Psi(L')dL' \tag{7}$$

to which must be added the mass in the water and sediment for the total mass of toxicant in the entire system.

Three water body types are of specific interest in the transport of hazardous substances: (a) a completely mixed lake or bay, (b) a one-dimensional non-dispersive river system and (c) a dispersive-advective estuarine system. Table 1 shows the appropriate equations, derived from Equation (4) for each of these cases. The inclusion of an additional independent vari-

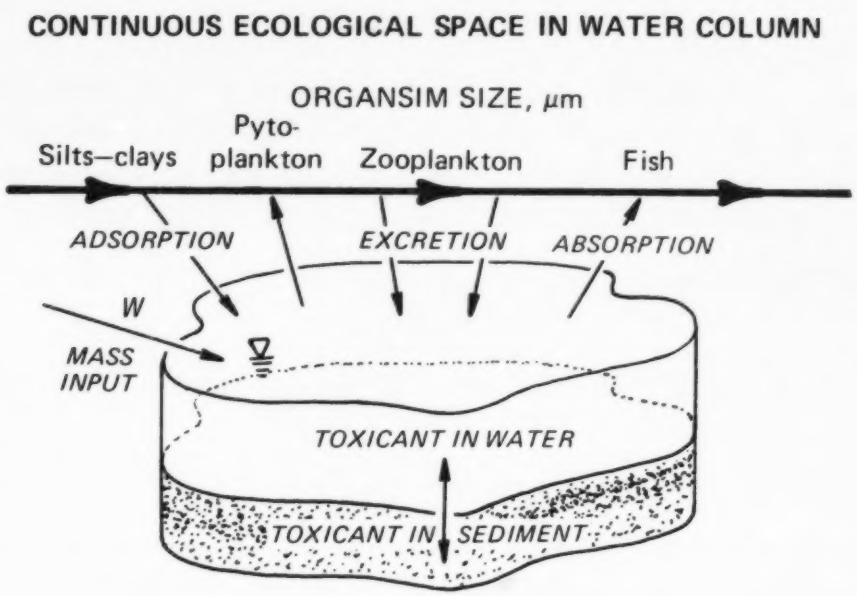


Figure 4. Schematic of General Model for Single Completely Mixed Water Volume

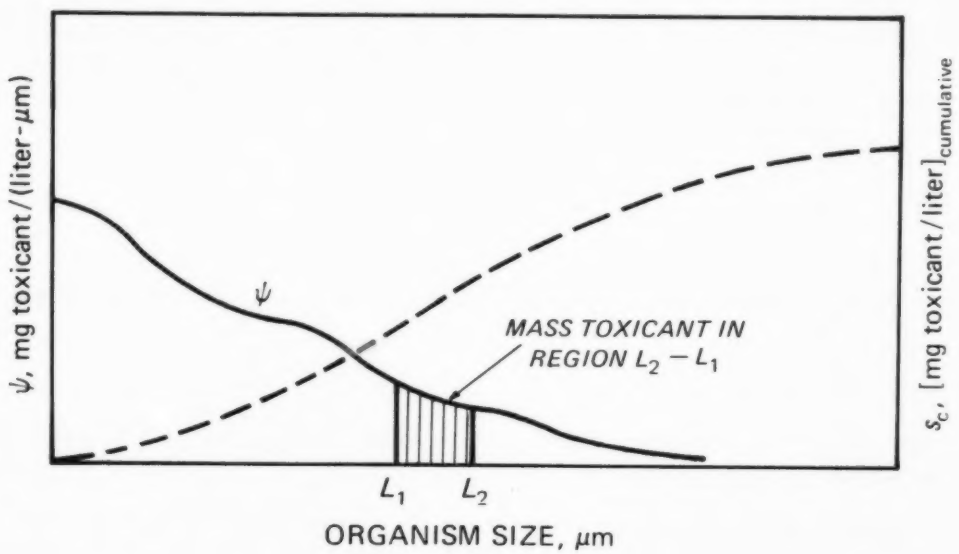


Figure 5. Density Function, Ψ and Distribution Function s_c

able, L, results in an added dimensionality to each equation. Thus, the completely mixed case, (which without L, would be represented by an ordinary differential equation) is represented by a partial differential equation. Similarly, the one-dimensional river case now also includes the additional ecological dimension resulting in a time variable partial differential equation in two dimensions. In this work, the completely mixed water volume is considered in some detail in order to develop the concepts and explore in a preliminary way, the meaning and determination of the model parameters and behavior.

TABLE 1

FORM OF HAZARDOUS SUBSTANCE TRANSPORT EQUATION
FOR DIFFERENT WATER BODY TYPES

Water Body Type	Assumptions	General Equation
Lake or Bay	Completely Mixed Volume - V	$V\frac{\partial \Psi}{\partial t} + V\frac{\partial v_L \Psi}{\partial L} = S(L,t)$
River	One-dimensional-no dispersion	$\frac{\partial \Psi}{\partial t} + \frac{1}{A}\frac{\partial Q\Psi}{\partial x} + \frac{\partial v_L \Psi}{\partial L} = S(x,L,t)$
Estuary	One-Dimensional-Dispersive, advective	$\frac{\partial \Psi}{\partial t} + \frac{1}{A}\frac{\partial Q\Psi}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(E_x A\frac{\partial \Psi}{\partial x}\right) + \frac{\partial v_L \Psi}{\partial L} = S(x,L,t)$

SECTION 5

THE COMPLETELY MIXED WATER VOLUME CASE

If in Equations (4) and (5) the water body is assumed to be well mixed, with no gradients in concentration, then the governing equation for Ψ, the toxicant density function is

$$V\left(\frac{\partial \Psi}{\partial t} + \frac{\partial v_L \Psi}{\partial L}\right) = Q\Psi_{in} - Q\Psi + W'(L) - S'(L) \qquad (8)$$

where Q = mass transport through volume V, Ψ_{in} = the input density function, W'(L) = sources of Ψ and S'(L) = sinks of Ψ. Equation (8) can be recognized as an advective equation or maximum gradient equation identical to that used in analysis of river systems but here derived for continuous organism size in a completely mixed volume. Since the equation has no dispersion terms, there is no "mixing" in the food chain.

The left hand side terms represent the rates of change of the density of the substance with time and organism size. The first term on the right hand side of Equation (8) is the mass transport of the density of the substance entering the volume. This would include the mass of toxicant distributed in the phytoplankton, zooplankton, and fish entering the completely mixed volume V.

The mass transport Q is a quantity that reflects the transport of the entire food chain and in general may be a function of L. For the passive regions of the food chain (e.g. non-motile phytoplankton), Q represents the water flow. For active regions (e.g. migratory fish), Q represents the transport of toxicant out of the volume due to the velocity of those particular regions. The sources and sinks are discussed below. The behavior of equations such as Equation (8) is well known. Solutions to distributed sources and sinks, variable coefficients and time variable situations are all obtainable. However, to provide a starting point some further assumptions are in order. Assume that:

1) the uptake of the toxicant is proportional to the water concentration c and the biomass along L,

2) excretion of the toxicant occurs from the entire food chain according to first-order kinetics on Ψ,

3) $\Psi_{in} = 0$, i.e. there is no input of toxicant mass associated with the food chain.

The assumption of proportional uptake to the water concentration is particularly important since it implies linearity with input loads. The literature on laboratory experiments for the upper levels of the food chain appears to justify this assumption. (For example, see Hansen et al, 1974, and Vreeland, 1974 for the linear uptake of PCB's with water concentration for pinfish and the American oyster.) However, in the micron and sub-micron range of particles (e.g. clays), the adsorption phenomenon is not necessarily linear and often varies logarithmically over wide ranges. For the description of a toxicant in the food chain however, the assumption appears reasonable, at least for the higher levels.

Under these assumptions, Equation (8) becomes:

$$V\left(\frac{\partial \Psi}{\partial t} + \frac{\partial v_L \Psi}{\partial L}\right) = -Q(L)\Psi - K(L)V\Psi + k_u(L)\, m(L)Vc \qquad (9)$$

and the water equation is:

$$V\frac{dc}{dt} = W - Qc - \lambda Vc + V\int_{L_1}^{\infty} K(L)\Psi dL - \left[\int_{L_1}^{\infty} k_u(L)m(L)\, dL\right]Vc \qquad (10)$$

where K is the excretion rate $[T^{-1}]$, k_u is the uptake rate $[(T\text{-}M(Biomass)/L^3)^{-1}]$, m(L) is a biomass density function $[(M(Biomass)/L^3) - L^{-1}]$, λ is the decay rate $[T^{-1}]$ for c due to photo-oxidation, radioactive decay or other mechanisms of breakdown. The parameters, Q, K, k_u and m may be complicated functions of L. For example, it is obvious that the whole food chain is not necessarily "flushed out" equally by the flow Q through the volume, V. Furthermore, the excretion rate may also vary along the food chain. It should also be noted that while Equation (9) is a partial differential equation, the water equation is an ordinary differential equation and Ψ appears only as a source term. The integral terms on the right side of Equation (10) represents the total excretion and uptake by the entire food chain of the toxicant to or from the water volume.

Equation (9) and (10) represent the interaction between the water concentration c and the distribution in the food chain given by Ψ. The flux of the toxicant due to excretion to the water phase is given by the fourth term on the right of Equation (10) while the uptake from the water by the distribution of biomass, m(L), with size, is given by the last term of Equation (10). In this form, the respon e is time variable and can incorporate time variable uptake and/or excretion due, for example to variable water temperature.

STEADY STATE

If a steady state is assumed in Equations (9) and (10), the following Equations (11) and (12) result:

$$\frac{dv_L \Psi}{dL} + K'\Psi = k_u(L)m(L)c \tag{11}$$

$$c = \frac{1}{G}\left[\frac{W}{V} + \int_{L_1}^{\infty} K\Psi dL\right] \tag{12}$$

where $K' = Q/V + K = 1/t_o + K$

(for $t_o = V/Q$, the detention time) (13)

and $G = Q/V + \lambda + \int_{L_1}^{\infty} k_u m \, dL$ (14)

In general, all coefficients are functions of L. Thus the detention time t_o represents the detention time of the entire food chain as well as the water. Note that Equation (11) is an ordinary differential equation while its coupled water equation is an algebraic equation that is easily solved once Ψ is known. Several important special cases of Equations (11) and (12) can now be explored.

CONSTANT COEFFICIENTS

Consider the organism size as divided into a series of regions each with constant coefficients but each region is still continuous. The continuous nature of the region distinguishes it from a compartment where a discretization is performed. Also assume that the mass density function m(L) is a constant in each region. Then Equation (11) for region i is:

$$v_{L_i} \frac{d\Psi_i}{dL} + K'_i \Psi_i = k_{ui} m_i c \qquad i = 1 \ldots r \tag{15}$$

Equation (12) is:

$$c = \frac{1}{G}\left[\frac{W}{V} + \sum_{i=1}^{r} K_i \int_{L_i}^{L_{i+1}} \Psi_i dL\right] \tag{16}$$

or $c = \frac{1}{G}\left[\frac{W}{V} + \sum K_i s_i\right]$ (16a)

and $G = Q/V + \lambda + \sum_{i=1}^{r} \int_{L_i}^{L_{i+1}} k_u m dL$ (16b)

If it is temporarily assumed that the water concentration is fixed and known, or that the contribution to c from the food chain is small, then the equations can be considered decoupled. The solution to Equation (15) for the first region therefore is:

$$\Psi = \frac{k_u mc}{K'} \left(1 - \exp\left(-\frac{K'}{v_L}(L-L_1)\right)\right) + \Psi_{o1}\exp\left(-\frac{K'}{v_L}(L-L_1)\right)$$

$$\text{for } L_1 \leq L \leq L_2 \tag{17}$$

where the subscripts for region 1 have been dropped and Ψ_{o1} is the initial value obtained from the preceding region in the food chain. The first term in Equation (17) represents the uptake from the water by the specific region of the food chain and subsequent transfer up the food chain via the velocity v_L. The second term represents the input of the toxicant from the preceding food chain region and subsequent transfer. Equation (17) can also be written as:

$$\nu = \frac{k_u c}{K'} \left(1 - \exp\left(-\frac{K'}{v_L}(L-L_1)\right)\right) + \Psi_{o1}/m_{12}\ \exp\left(-\frac{K'}{v_L}(L-L_1)\right) \tag{18}$$

where ν has units (Mass(Toxicant)/Mass(Biomass), i.e., a bioaccumulation factor. The quantity ν is a measure often used in assessing levels of hazardous substances in the food chain for possible regulatory action. Figure 6 shows the relationship between Ψ, m and ν. Note that the second term involves the mass density for the region between L_1 and L_2, m_{12}, which indicates that as the mass density decreases with increasing movement up the food chain, the initial condition of the toxicant will be altered by the ratio of the adjacent biomass density. This can be seen if it is assumed that Ψ has reached its equilibrium value in the region preceding L_1 to L_2. Then:

$$\Psi_{o1} = \frac{k_u\ c\ m_{01}}{K'_{01}}$$

and $\nu_1 = k_u c/K'_{01}$ is the bioaccumulation factor in the region L_o to L_1. Then in Equation (18):

$$\nu = \frac{k_u c}{K'} \left(1-\exp\left(-K'/v_L(L-L_1)\right)\right) + \nu_1 \frac{m_{01}}{m_{12}}\ \exp\ \left(-K'/v_L(L-L_1)\right) \tag{19}$$

This equation shows the effect of the varying biomass density along the food chain. A 50% decrease of mass density from region L_0 to L_1 doubles the initial bioaccumulation factor in region L_1 to L_2.

The difficulty with the simple model of Equation (19) is that the biomass density function is usually decreasing rapidly with L. Thus a large number of regions would be required or abnormally unrealistic discontinuities would occur at the boundaries of the ecological regions. A simple extension of Equation (15) is to assume that:

$$m_i(L) = (m_o)_i \exp(-(b/v)_i L) \tag{20}$$

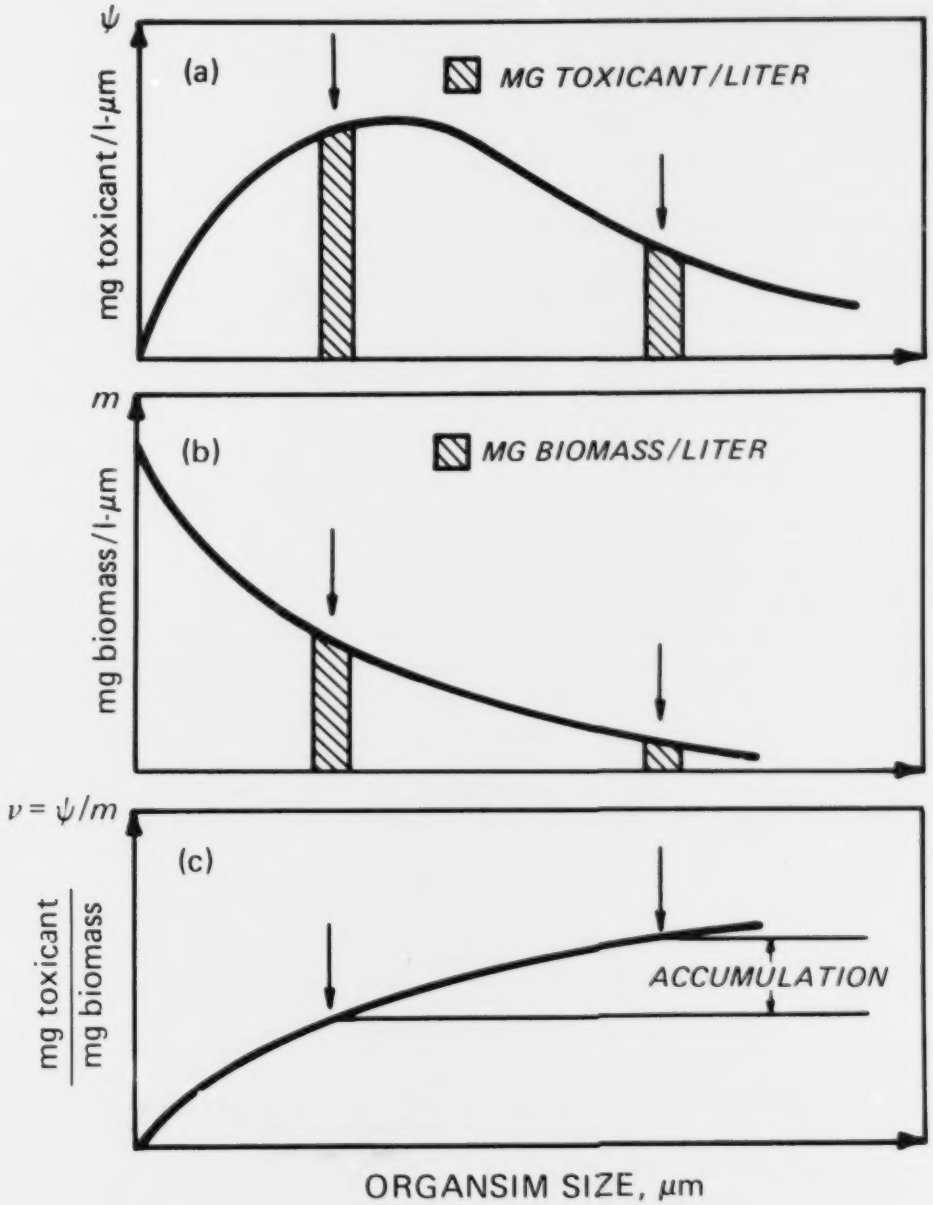


Figure 6. a) The Toxicant Density Function, b) The Biomass Density Function and c) The Bioaccumulation Function

Thus, the differential equation is now forced by an exponentially decreasing biomass density function which eliminates discontinuities at region boundaries. The solution for a given region is:

$$\Psi = \frac{k_u c m_o}{K'-b}(\exp(-bL/v_L) - \exp(-K'L/v_L)) + \Psi_{o1}\exp(K'L/v_L) \qquad (21)$$

but since m is given by Equation (20),

$$\frac{\Psi}{m} = \nu = \frac{k_u c}{K'-b}(1 - \exp(-((K'-b)/v_L)L)) + \nu_1\exp(-((K'-b)/v_L)L) \qquad (22)$$

Note that this equation is identical in form to Equation (18) except that the coefficient K' is reduced by b. Equation (22) is to be preferred since there are no mass discontinuities and hence a "smooth" calculation can be made of the bioaccumulation factor as a function of trophic length. The structure and meaning of Equation (22) is displayed in Figure 7.

As shown in Figure 7, three ranges of organism size are assumed. The variation of the mass density is given by the three exponential functions in Figure 7(a). The two components of the bioconcentration factor given by Equation (22) are shown: the effect due to food chain transport from the preceding region and the effect due to uptake from the water and subsequent accumulation within the region.

The water equation associated with this case is given from Equation (16) together with Equations (20) and (21). Equations (16) and (22) form the basic steady state model. These coupled equations can then be solved using an iterative approach on the water concentration for given external input conditions. Successive application of Equation (22) through any number of regions in ecological space permits computation of the distribution of the bioaccumulation of the toxicant. Equation (16) which includes the external mass input of the toxicant, W, permits the concentration of the "maximum permissible" discharge so as not to exceed toxicant levels at any point in the food chain. Furthermore, these equations incorporate the physical as well as biochemical interactions, as for example, between water detention time, selective uptake and variable excretion. Yet, the entire food chain is easily computed via Equation (22) in contrast to the special case of homogeneous compartments which requires simultaneous solution of algebraic equations.

VARIABLE COEFFICIENTS

It is known that the metabolism of organisms is related to the size or mass of the organism (Eberhardt 1968, 1969). Norstrom et al. (1976) in their work on a model of bioaccumulation recognized and incorporated, for example, a log-log relationship of methylmercury and PCB clearance rates for fish over the weight range of 1-300 gms. Additional extensions of these and other data are discussed below where it is indicated that a log-log relationship of clearance rate with organism length is justified. Further, since the velocity of transfer up the food chain is related to the grazing or predation rate, it is reasonable to assume that v_L also depends on the organism length.

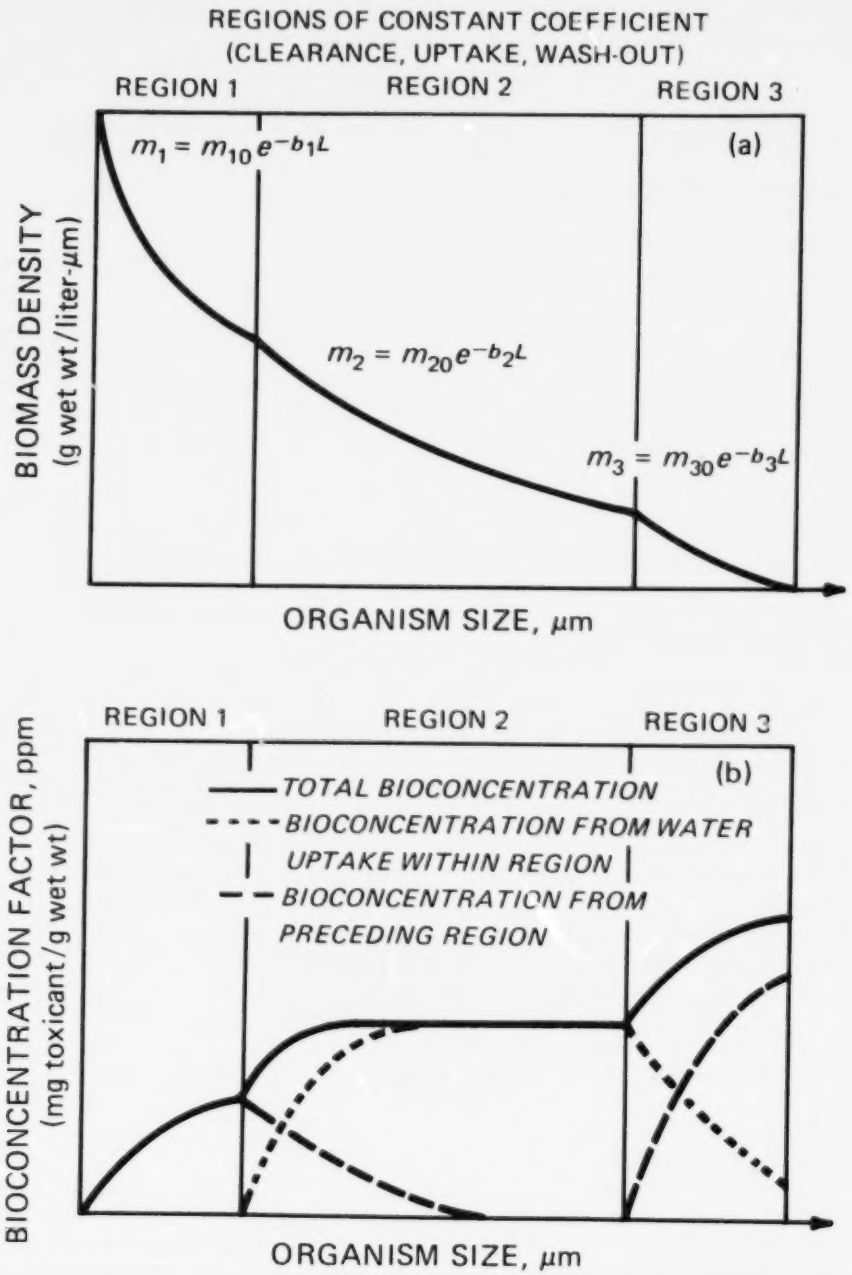


Figure 7. A Three Region Model a) Variation of Biomass Density
b) Components of Bioconcentration Factor

The uptake rate for some substances might also be expected to be related to the size of the organism, as for example, through the mass of lipids which in turn would result in differential solubilization of a substance.

Obviously, with all coefficients varying as complicated functions of organism size, a direct analytical solution of all functions of interest would become cumbersome and unwieldy. However, the lessons learned in modeling advective water quality systems can be applied here. The principal lesson learned there is that for many practical applications the problem is best handled by assuming constant coefficients over certain regions in space as in the previous case. Since the variation in key parameters is significant over ecological space, the preceding case can be extended to include logarithmically varying coefficients together with variable biomass density. The resulting solutions can then be integrated numerically.

Thus let:

$$K = a_1 L^{b_1} \tag{23a}$$

$$v_L = a_2 L^{b_2} \tag{23b}$$

$$m = a_3 L^{b_3} \tag{23c}$$

The mass balance equation in Ψ is then:

$$\frac{\partial v\Psi}{\partial L} + (Q/V + K)\Psi = k_u a_3 L^{b_3} c \tag{24}$$

with K and v_L given by (23a) and (23b) and k_u assumed constant. This equation is a variable coefficient linear equation with a variable distributed input. The solution (see, for example, Thomann, 1972) is given by:

$$\Psi = [\Psi_1 + I(L)] \exp [\phi(L)] \tag{25}$$

where:

$$\phi(L) = \alpha_2[L^{\alpha_1} - L_1^{\alpha_1}] + b_2 \ln L/L_1 + \frac{Q}{Va_3b_3} (L_1^{(1+b_3)} - L^{-(1+b_3)}) \tag{25a}$$

$$I(L) = \frac{k_u c a_3}{a_2} \int_{L_1}^{L} L^{b_3 b_2} \exp(\phi(L))\, dL \tag{25b}$$

$$\alpha_1 = 1 + b_1 - b_2 \tag{25c}$$

$$\alpha_2 = a_1/\alpha_1 a_2 \tag{25d}$$

If data were available on the power laws of Equation (23), then Equation (25) provides the density of the toxicant throughout the food chain without resort to the designation of constant regions.

SECTION 6

DATA ANALYSIS

LABORATORY DATA ANALYSIS

The continuous model, which uses trophic length as a measure of ecological dimensionality provides a framework for a vast array of experimental data that have been obtained on the fate of hazardous substances. The laboratory experiments generally fall into three categories:

1) Bioconcentration and clearance tests using single organisms
2) Uptake and subsequent transfer from one organism to a second (and third) organism in a "one-dimensional" aquarium test
3) Aquaria simulations of "model" ecosystem food webs.

In each category, the test may include input of the hazardous substance directly into the water, indirectly through sediment that has a fixed concentration of the toxicant or through "spiked" food. In terms of the continous model, these laboratory experiments appear as delta functions along the organism size scale and permit estimates of model parameters at fixed organism lengths. Thus, if an experiment is conducted on the uptake and clearance rates of mature Daphnia magna, this provides an estimate for the given substance at an L of about 4,000 μm (4mm). The model indicates that if laboratory data of the first category are plotted as functions of organism size then estimates of $k_u(L)$ and $K(L)$ can be obtained. Data of the second category permit estimates of $v_L(L)$ and data of the third category permit determination of all the model coefficients under a simplification of a complex web to a one-dimensional system.

Table 2 shows the range of sizes for different components of the aquatic system. From the bacterial level to the higher organisms of large animals and man, the total range is some six orders of magnitude. Although there is considerable overlap in the components (especially between mature forms of one component and immature forms of another), various regions of the length scale do admit of some approximate ecological interpretation.

WATER UPTAKE AND EXCRETION - SOME ILLUSTRATIONS

As an illustration, data have been compiled on the variation of PCB water uptake and clearance rates. The relationship with length of the organism is shown in Figures 8 and 9 and Tables 3 and 4. From Equation (22) and a single organism length, the water uptake data as reported in the literature represents the ratio of uptake to clearance, $k_u/K = N$, the bioconcentration function. Figure 8 indicates a range of bioconcentration factors with orga-

TABLE 2

RANGE OF ORGANISM SIZES

Component	Approx. Size Dimension (μm)
Physical	
Medium Clay	0.5 - 1
Silt	1 - 20
Sand	20 - 150
Biological	
Virus, poliomyelitis	0.25
Bacteria	0.5 - 3
Fungi	2 - 20
Protozoa	
Flagellates	10 - 50
Ciliates	30 - 200
Algae, Blue-green	5 - 20
Diatoms, green algae	10 - 100
Zooplankton-rotifers	50 - 200
Nauplii	100 - 500
Crustaceans	400 - 4000
Fish; small, immature	1000 - 10^4 (1mm-1cm)
Fish; medium, juvenile	10^4 - 10^5 (1cm-.1m)
Fish; large, mature	10^5 - 10^6 (0.1m-1m)
Man - 6 ft.	$10^{6.25}$

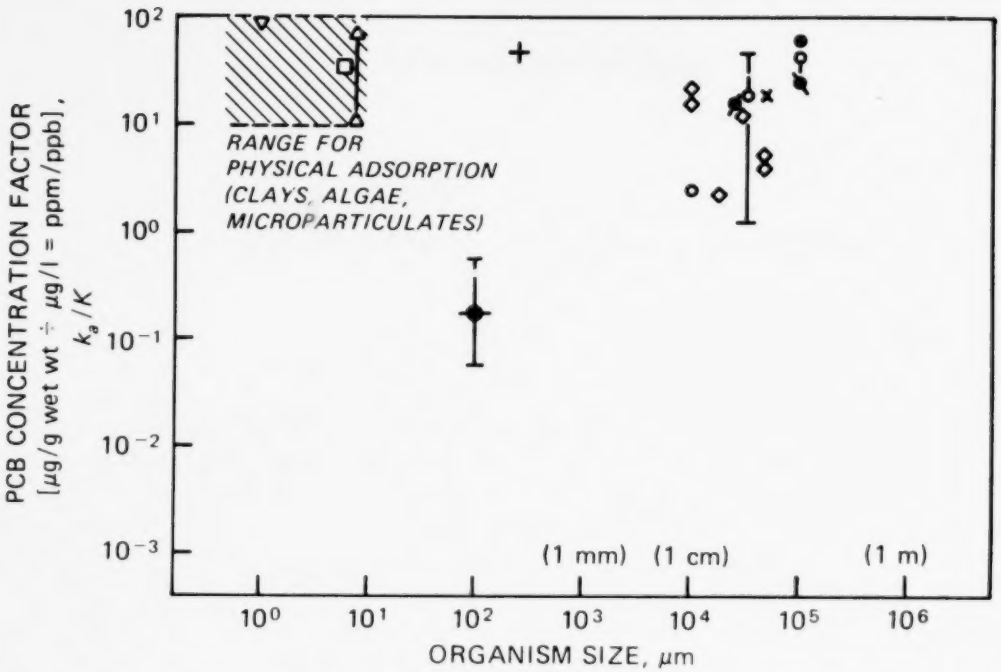


Figure 8. Variation of PCB Uptake With Organism Size From Water Only

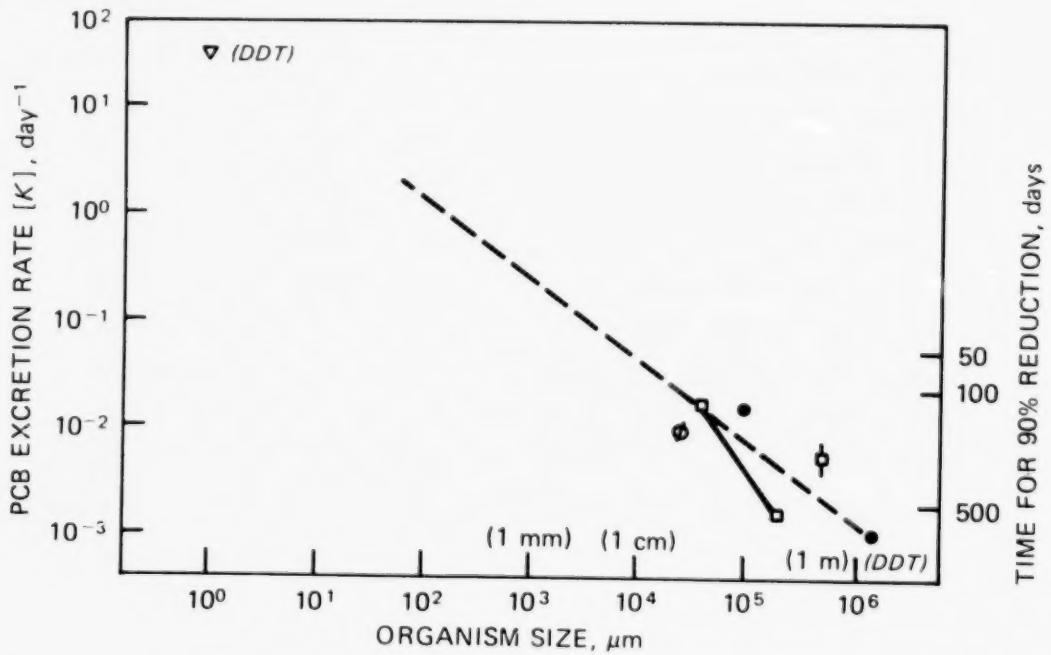


Figure 9. Variation of PCB and DDT Excretion With Organism Size

TABLE 3

EXPLANATION OF SYMBOLS FOR FIGURE 8
PCB CONCENTRATION FACTORS[1]

Symbol	Organism or Organism Group	PCB Analyzed	Reference
●	Spot (Leiostomus xanthurus)	Aroclor 1254	Moriarty (1975)
○	Mayfly nymth (Ephemera danica)	Clophen A 50	Sodergren and Svensson (1973)
◐	Oyster (Crassostrea virginica)	Isomer Mixture	Vreeland (1974)
⌀	Pinfish (Lagodon rhomboides)	Aroclor 1016	Hanson et al (1974)
◥	Spot (Leiostomus xanthurus)	Aroclor 1254	Duke and Dumus (1974)
♀	Minnow (Cyprinodon variegatus)	Aroclor 1254	Hansen et al (1973)
◊	Aquatic invertebrates; midge, scud, mosquito larvae, stonefly dobsonfly, crayfish	Aroclor 1254	Sanders and Chandler (1971)
+	Daphnia magna	Aroclor 1254	Sanders and Chandler (1971)
×	Pink shrimp (Penaeus duorarum)	Aroclor 1254	Nimmo et al (1971)
⊕	Protozoa (Tetrahymena pyriformis)	Aroclor 1254	Cooley et al (1972)
◻	Algae (Chlorella)	Clophen A 50	Sodergren (1977)
△	Marine phytoplankton - natural assemblage	Isomer Mixture	Biggs et al (1977)
▽	Particulates - Duwamish Estuary - Hudson River		Hafferty et al (1977) Unpublished

[1] All tests on whole organisms or corrected to whole organisms

TABLE 4

EXPLANATION OF SYMBOLS FOR FIGURE 9
PCB EXCRETION RATES (1)

Symbol	Organism or Organism Group	Excretion Measurement	PCB Analyzed	Reference
•	Spot (Leiostomus xanthurus)	whole organism	Aroclor 1254	Moriarty (1975)
✖	Man	Adipose tissue	DDT	Moriarty (1975)
⊕	Rhesus monkey	-	-	Allen et al (1974)
⊄	Pinfish (Lagodon rhomboides)	whole organism	Aroclor 1016	Hansen et al (1974)
□[2]	Yellow perch (Perca flavescens)	whole organism	Aroclor 1254	Norstrom et al (1976)
▽	Bacteria (Aerobacter aerogenes, Bacillus subtilis)	whole organism	DDT	Johnson and Kennely (1973)

(1) Note that some DDT excretion factors have been included

(2) Estimated from field data

nism size and except for one point does not appear to show any functional relationship with size. If that point is accepted, however, then a rough approximation for the bioconcentration factor is:

$$N_{PCB} = \left(\frac{k_u}{K}\right)_{PCB} \simeq .01L^{.7} \tag{26}$$

for L in m and k_u/K in $(gm/l)^{-1}$ and N_{PCB} is the bioconcentration factor for PCB in µg PCB/gm wet wt ÷ µg/l. The bioconcentration factor could also be taken as a constant over the entire size range at a value of approximately 50 µg PCB/gm ÷ µg/l. This implies that k_u and K have the same slope in L. Also, as an approximation, from Figure 9,

$$(K)_{PCB} \simeq 80L^{-.8} \tag{27}$$

for K in $(day)^{-1}$ and L in µm. Thus:

$$(k_u)_{PCB} \simeq 0.8L^{-.1} \tag{28}$$

for the case of Equation (26) and

$$(k_u)_{PCB} \simeq 4000L^{-.8} \tag{28a}$$

for a constant N of 50. These are only approximate relationships since the available data are somewhat variable. The model framework does not require any specific functional form and these forms essentially provide a first estimate of the rate parameters, k_u and K. It is interesting to note though that the data of Figure 8 include a variety of organisms such as molluscs, larger crustaceans, small and large fish and even some terrestial organisms. The data on physical adsorption of PCB are included to illustrate the extension of the theory to include concentration on microparticulates, including phytoplankton. Indeed for substances such as PCB with relatively low water solubility, adsorption onto particles in the range of 1-100 µm is quite common. As reviewed by Wilson and Forester (1973), such particles would also include particulate organic detritus and phytoplankton although one might suspect different adsorption properties for organic particles in contrast to the inorganic particles, such as clays. Adsorption experiments such as given by Haque et al (1974) indicate decreasing concentration factors with increasing particle size and shows that the adsorption phenomenon is fundamentally a phenomenon of physical chemistry as opposed to the interactions occurring in the process of bioaccumulation. For example, for DDT adsorption, Hargrave and Phillips (1974) determined that

$$N_{DDT} = 3541\ L^{-1.70} \quad 1\mu m \leq L \leq 1{,}500\ \mu m$$

for N_{DDT} = µg DDT adsorbed/gm dry weight ÷ µg/l which shows a rapid drop with increasing particle size. Also, this relationship is greater than that for PCB by about an order of magnitude. The theory for the model being used here can apparently be extended to include some representation of the adsorption

of a toxicant onto microparticles. Such an extension, however, is not explored here.

Table 5 summarizes some relationships of k_u/K and K; the bioconcentration factor and the excretion rate for different substances. Note should be taken of the fact that the range of organism sizes over which data were available limits the overall comparison of the relationship between the substances. Nevertheless, the accumulation of methyl mercury (as a function of length) is somewhat less relative to PCB and DDT. Thus, at $L = 10^5$ μm, the k_u/K ratio for mercury is 3.9 in contrast to the PCB ratio of 32 at the same length.

FIELD DATA ANALYSIS - PCB's IN LAKE ONTARIO

The laboratory data discussed above provide estimates of k_u and K as a function of organism size. In the basic steady state model of Equation (22), the parameters v_L and b must also be known. At present, it appears that experimental data are not available to permit independent estimation of the velocity transfer coefficient, v_L which would require feeding experiments over a range of organism size. Nevertheless, estimates of b/v_L can be obtained from field data on the distribution of biomass with particle size. With data available and the toxicant concentration for various levels in the food chain, an estimate can be made of the components of Equation (22) although such an estimate will not be completely independent of the data itself. The analysis of the modeling framework at this stage therefore does not constitute a verification of the model, but a type of first calibration. The primary benefit of such an analysis is that it places the available field and laboratory data in an analytical framework to gain further insight into the nature of the accumulation of hazardous substances in the food chain. In order to illustrate the use of the model in this type of setting, the concentration of PCB's in Lake Ontario is analyzed.

AVAILABLE DATA ON LAKE ONTARIO

As part of the IFYGL Program, Haile et al. (1975) have obtained data on the PCB concentrations in Lake Ontario fish, water, sediment, net plankton, Cladophora and benthos. Their results together with data obtained by the Ontario Ministry of the Environment (1976) are summarized in Table 6. The data on a wet weight basis show a general bioaccumulation of PCB's from the smaller organisms to the larger coho salmon. The data on the salmon are generally from inshore stations while the data on net plankton and the alewife group include both inshore and open lake stations. As noted by Haile et al. (1975), the water data includes both dissolved and micro-particulate fractions. However, following the work of Zitko (1974) who showed that PCB's on suspended solids can be bioaccumulated by juvenile Atlantic salmon, it is assumed that the total PCB concentration in the water is available to the food chain. The size ranges in Table 6 that were assigned to each component are somewhat arbitrary, although realistic. As noted in Section V, such a division is simply a convenience in computing the simpler steady state model of Equation (22).

TABLE 5

SOME RELATIONSHIPS BETWEEN UPTAKE AND EXCRETION AND ORGANISM SIZE(1)

Substance	$k_u/K = a_1 L^{b_1}$		$K = a_2 L^{b_2}$		Size Range of Data (μm)	References(2)
	a_1	b_1	a_2	b_2		
PCB	.01	0.70	80	-.80	10^4-$10^{5.5}$	1-8
DDT	.45	0.35	15.8	-.64	10^0-10^6	1,2,5,9,10,11
Methyl Mercury			132	-.90	10-10^6	1,12-18

(1) k_u/K - μg/gm wet wt μg/l; K - 1/day; L - μm

(2) References:
1. Moriarity (1975)
2. Sodegren and Svensson (1973)
3. Vreeland (1974)
4. Hansen et al (1974)
5. Duke and Dumas (1974)
6. Hansen et al (1973)
7. Haque et al (1974)
8. Norstrom et al (1976)
9. Reinert et al (1974)
10. Johnson and Kennedy (1973)
11. Johnson et al (1971)
12. de Freitas et al (1974)
13. Livingston (1975)
14. Hartung (1976)
15. Sloan et al (1974)
16. Hardcastle and Mavichakana (1974)
17. Burrows and Krenkel (1973)
18. Cross et al (1973)

TABLE 6

SOME DATA FOR LAKE ONTARIO

PCB CONCENTRATION (AROCHLOR 1254 EQUIVALENT)

Component	Average	Std. Deviation	Assumed Range of Organism Size
	(μg/gm(wet wt))		(μm)
Net Plankton[1] (64 μm mesh)	0.72	0.35	100 10^4
Alewife, smelt[1] slimy sculpin	3.24	2.14	10^4 $2.5 \cdot 10^5$
Coho Salmon[2]	6.47	2.85	$2.5 \cdot 10^5$ 10^6
Water (1,3)	55.4	21.1	

(1) Haile et al (1975) (2) Ont. Min. Env. (1976)
(3) Concentration in ng/l, dissolved + particulate, <64μm

Data on biomass throughout the entire food chain are somewhat limited especially in the upper trophic levels. This is due partly to the difficulty of obtaining reliable estimates for fish biomass. However, at the lower end of the organism size scale, data are available from particle counts given by Stoermer et al. (1975) and from acoustical measurements made by McNaught et al. (1975). Stoermer's data cover the range from 5 to 150 μm and McNaught's data span the region from 800 μm to about 5,000 μm. The lower range therefore provides data on particle density in the region <64 μm, the mesh size used by Haile et al. (1975). The data for 800 μm to 5,000 μm provide biomass information on the net plankton.

The estimated mass density function is obtained from

$$m_{i+1} = \frac{c_{i,i+1}}{L_{i+1} - L_i} \qquad i = 1....\eta \tag{29}$$

where $c_{i,i+1}$ is the concentration (e.g. number particles/100 ml) in the size range L_i to L_{i+1} (μm), l is the total number of size ranges and m_{i+1} is the mass density for the region in concentration units/μm, plotted at the end of the region. Figure 10 shows a semi-log plot of the mass density estimates as a function of particle size. As shown, the results of this limited analysis of the particle and acoustical data indicate regions where one might assume an exponential decrease in biomass density as given by Equation (20). Note also that the biomass density drops by several orders of magnitude over the range of the data. The slope of the density function, b/v_L [μm^{-1}] is a ratio of model coefficients required by Equation (22). The quotient represents the ratio of biomass respiration to the rate at which biomass is transferred up to higher trophic levels via predation. The model requires the slope of the density function over the entire length scale. Thus, the data of Figure 10, were used to extrapolate the slope of the density function out to the upper limit of 10^6 μm. This is admitedly a hazardous(?) extrapolation and illustrates the need to obtain biomass data throughout the food chain. The relationship for the mass slope using Figure (10) is therefore:

$$b/v_L = 6.3\ L^{-1.05} \tag{30}$$

for b/v_L in $[\mu m]^{-1}$ and L in μm. Equation (30) was used to estimate b/v_L for the food chain Equation (22).

The organism size range for Lake Ontario was divided into three continuous regions: 10^2-10^4μm; 10^4-2.5 10^5μm; 2.5 10^5-10^6μm. These regions are not compartments in the classical sense but are rather continuous domains with constant coefficients. Estimates of k_u, K for PCB's were used from Figures 8 and 9 in Equation (22) to obtain a good correlation to the observed data. This provided estimates of the coefficient groupings:

$$k_u/(K'-b) \text{ and } (K'-b)/v_L$$

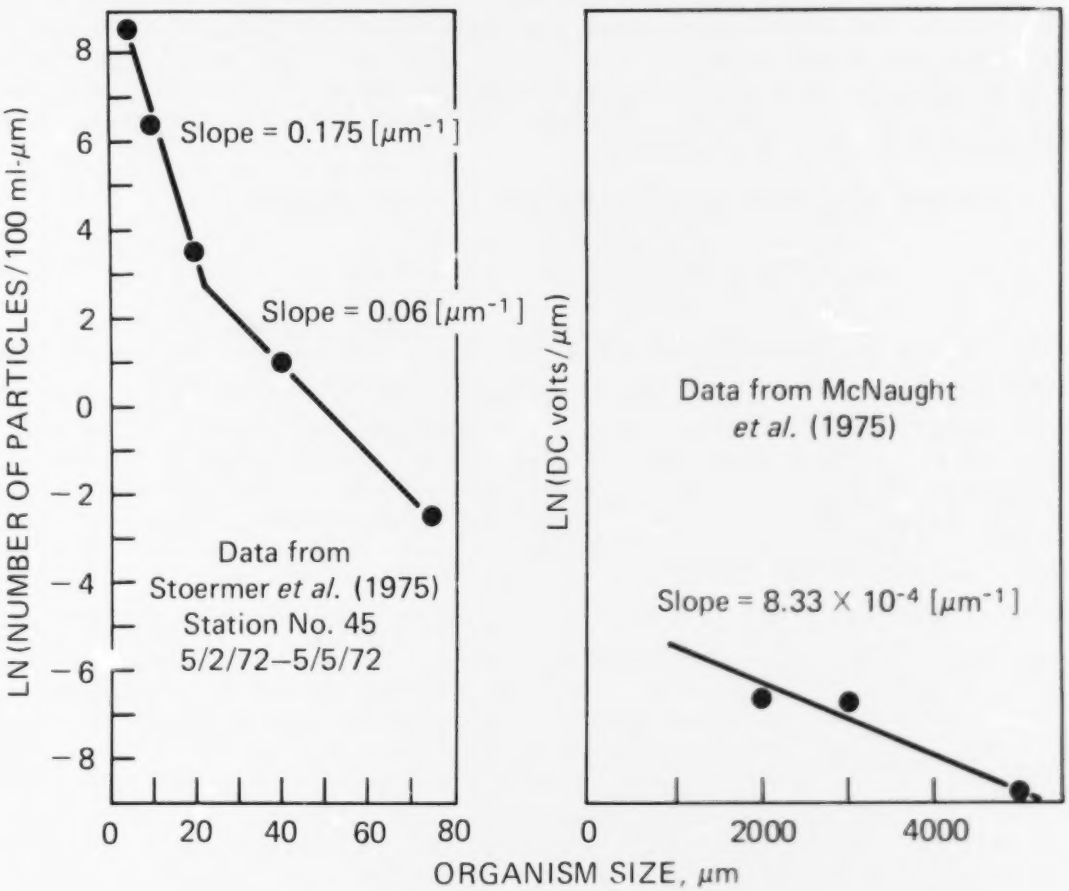


Figure 10. Lake Ontario Mass Density as a Function of Organism Size

The first group, $k_u/(K'-b)$ was used to obtain an estimate of $K'-b$ which together with the second coefficient $K'-b/v_L$ was used to obtain v_L. Then, given b/v_L from the mass density data, b was estimated. This value was then used with the original estimate of $K'-b$ to close the estimation procedure on K'. The "free" parameter was therefore v_L but an external check on the magnitude of v_L was provided by the b/v_L ratio from the biomass data.

The results of applying Equation (22) to the PCB data of Table 6 are shown in Figure 11 and the associated coefficients are given in Table 7. The two principal mechanisms of the steady state model are shown in Figure 11. The uptake directly from the water and subsequent transfer (the first term of Equation (22)) is seen to increase with increasing organism size. At the upper levels, the excretion rate is low, transfer velocity has increased and a rapid rise is calculated for the PCB concentration. Figure 11 also shows the residual PCB transferred from lower food chain levels. Again, because of the decreased excretion rate, increased transfer velocity through the food chain and the reduced mass density at the higher levels, PCB concentrations are retained over the larger segments of the food chain.

Figure 11 shows that for the salmon, about 33% of the observed 6.5 µg PCB/gm fish is due to transfer from lower levels in the food chain and about 67% from direct uptake. The build-up of PCB's therefore in the Lake Ontario ecosystem is postulated to be due to a complex interaction between water uptake rate, excretion rate, rate of transfer through the food chain and decrease of mass density with organism size. It should also be recalled that the toxicant concentration in the food chain is linearly related to the water concentration which in turn (Equation 23) is linearly related to the input PCB mass loading. In principle, then, one could estimate the required input loading such that a given level of PCB concentration would not be exceeded in any region of the food chain. However, sufficient data are not yet available on the present input to Lake Ontario to permit such a definitive calculation. Before such a calculation is made it would be preferable to estimate the water concentration independently of the measured values given input mass loading and estimates of removal rates.

However, one can estimate the total <u>water</u> (dissolved and microparticulate) concentration that would be necessary so as not to exceed certain levels in the food chain, if the coefficients used herein are considered reasonable. If 5 µg PCB/gm wet wt. is used at 10^6 µm as a level, than the water concentration would have to be about 36 ng/l or about 66% of the present 55 ng/l.

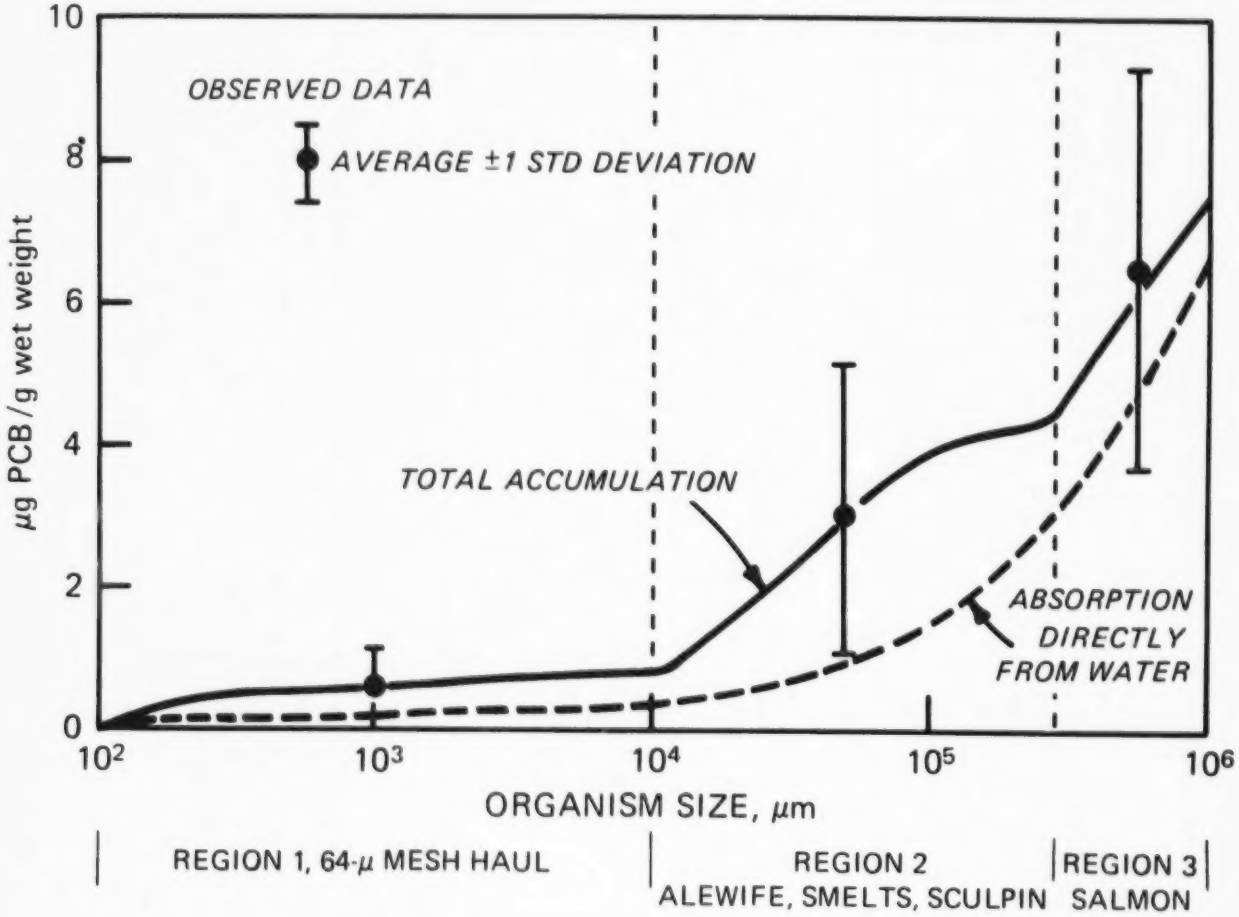


Figure 11. Analysis of PCB's in Lake Ontario

TABLE 7

COEFFICIENTS USED IN ANALYSIS OF PCB DATA WITH STEADY STATE SIZE DEPENDENT MODEL

Coefficient	Trophic Region 1 10^2-10^4 μm	2 10^4-$2.5 \cdot 10^5$ μm	3 $2.5 \cdot 10^5$-10^6 μm
Water Uptake - k_u $(gms/l\text{-}day)^{-1}$	0.5	0.38	0.23
Excretion - K' $(day)^{-1}$	0.05	0.0072	0.0025
Transfer Velocity - v_L (μm/day)	12	190	728
Biomass Respiration - b $(day)^{-1}$	0.01	0.0024	0.001
$(K'-b)/v_L$ $(\mu m)^{-1}$	$3 \cdot 10^{-3}$	$2.5 \cdot 10^{-5}$	$2 \cdot 10^{-6}$
$k_u/(K'-b)$ $(gm/l)^{-1}$	13.4	79	158

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